FY02 EXPLORATORY RESEARCH (ER) PROPOSAL STUDY OF OPEN-CHARM PRODUCTION AT RHIC

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Abstract

There will be prolific production of heavy quarks (charm and bottom) in central Au-Au collisions at the Relativistic Heavy-Ion Collider (RHIC). The charm quark in particular is the object of intense theoretical interest in connection with the search for the quark-gluon plasma and provides one of its most robust and anticipated signals -- suppression of the J/ψ resonance. Yet none of the four current detectors has the capability of detecting heavy quarks via the standard technique of finding detached decay vertices.

We propose to establish the capabilities of, and conceptual design for, a micro-vertex detector associated with the PHENIX muon spectrometers at RHIC. The new physics agenda would include the spin structure of the nucleon, heavy-quark production in proton-nucleus interactions, as well as the most difficult technical problem -- identification of open-charm production in central Au-Au collisions.

In the first two years of the proposal we would establish the optimal configuration for the micro-vertex detector. We would also select among the existing technologies and begin prototyping components utilizing P25's silicon detector test facility in SM-218. The final year would be devoted to more advanced prototyping and to writing a DOE proposal for the construction of the full-scale device for the PHENIX detector.

I. Introduction and Proposed Objectives

Brookhaven's Relativistic Heavy-Ion Collider (RHIC) will start its second cycle of operation in May 2001 with collisions of Gold ions at 200 GeV per nucleon center-of-mass energy ($\sqrt{S}$) -- far higher than the CERN SPS program which has run for 15 years at $\sqrt{S} = 17$ GeV/A. At RHIC there is no doubt that the extreme energy densities (≥ 1GeV/fm^3) required to achieve quark de-confinement will be reached. Thus RHIC is a truly unique facility, providing capabilities qualitatively different from other accelerators. New physics is practically guaranteed. On the other hand, there is every reason to be skeptical that the new physics will emerge early on.

It was only in the final years of the CERN SPS program that measurements were made that could be called compelling -- the observation of "anomalous" suppression of J/ψ

production in central Pb-Pb collisions [1]. This observation was foremost on the list which led CERN management to announce last summer that a "new state of matter" had been created in the laboratory, a statement greeted with considerable skepticism by the international physics community. The CERN experimenters measuring J/ψ suppression did not have an ironclad case. Among the major issues not resolved was the possibility that the production of charm quarks[1] is, itself, suppressed. This would then imply that J/ψ suppression was not an indication of formation of the quark-gluon plasma (QGP), but was a consequence of other, perhaps more mundane, physics.

The first muon spectrometer of the PHENIX detector has been completed, and will be operational during the second RHIC running period beginning in May 2001. The heart of the muon spectrometer is the muon tracking system, designed and built by a collaboration led by P-25 staff. This spectrometer will provide the first data for J/ψ production at RHIC. It is not an exaggeration to say that this measurement is near the top of everyone's list of priorities.

However, neither PHENIX nor the other three RHIC detectors will have the capability of direct observation of charm quark production. The environment of nucleus-nucleus collisions presents significant challenges to the development of workable micro-vertex detectors. These challenges (discussed below) plus the complexity and expense of fielding such devices weighed heavily against including them in the baseline collider detectors at RHIC. Thus micro-vertex detectors will be a second-generation capability at RHIC. It is the development of such a device for the PHENIX muon spectrometers that is the focus of this proposal.

Section II introduces micro-vertex detectors in the context of the RHIC program. Sections III-V describe three independent areas of physics that the development of this technique would impact. Finally, Section VI outlines the current state of micro-vertex detector technology and presents a brief statement of the work to be accomplished.

II. Micro-vertex detection: The key to heavy-quark physics

When pairs of c and c̄ quarks are produced in high-energy collisions, only a few percent end up as bound states of charmonium (the spectrum of cc̄ bound states of which the J/ψ is the most readily observed). A far more likely outcome is for the c and c̄ to combine with lighter quarks to form long-lived "charmed" hadrons. Charmed hadrons decay to non-charmed hadrons with a lifetime characteristic of the weak interaction ($\approx 10^{-12}$ seconds.) The comparatively long lifetime combined with relativistic speeds confers a distinct signature to charm-quark decays -- they occur ten to hundreds of microns away from the point of production. This feature has been used extensively in the past 15 years at high-energy accelerators, where micro-vertex detectors have been employed to measure the properties of c-quark and b-quark hadrons. Micro-vertex detectors rely on silicon strip

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[1] The J/ψ resonance is a bound state of a charm and anti-charm quark

and pixel detector technology. They typically involve from ten thousand to over a million channels of electronic readout. Thus they are neither simple to build nor to operate.

Our group built and operated a ten thousand channel micro-vertex detector for a fixed-target experiment at Fermilab several years ago [2,3]. With this device we made the only direct observation of the nuclear dependence of open-charm production in proton-nucleus collisions. This experiment, which was carried out in a fixed-target environment, is a template for the kind of measurement that we believe is crucial to the RHIC program. We have also been responsible for the design of large silicon trackers at the SSC (2.5 million channels), CERN and the PHENIX multiplicity and vertex detector.

It is clear that now is the time to re-evaluate micro-vertex detector technology at RHIC. There are two main reasons. First, the RHIC program now includes some very interesting areas of physics where a micro-vertex detector could have significant impact, and for which the purely technical problem of finding displaced vertices is from one to three orders of magnitude simpler than for the central Au-Au collisions of the QGP search. Thus there is physics to be had along the way to development of the ultimate device. Two such physics cases are briefly described below. Second, vertex-detector and the associated electronic-readout technology have not stood still in the past ten years (see discussion below). Developments, driven by collider detectors at Fermilab and those under construction for LHC, have reduced the cost per readout channel by about an order of magnitude.

III. Charm and beauty physics in polarized p-p collisions

The polarized proton collider program at RHIC became real in 1995, with the investment of significant funding from the RIKEN Laboratory in Japan. This investment supports the construction of a second muon arm and other upgrades to PHENIX and RHIC. Important parts of the physics program include measurements of the anti-quark and gluon polarizations in the proton. These are vital data for solving the puzzle of the "missing" spin of the proton. (Existing measurements of the valence quark polarizations only account for about half of the proton's spin!) The RHIC spin program is now scheduled to start with low-luminosity polarized p-p operation this year.

The unambiguous identification of c- and b-quark production in polarized p-p collisions is a natural first application of a vertex detector for PHENIX. The physics program is the determination of the helicity of the gluon distribution of the proton. The perturbative diagram $g+g \rightarrow Q+\bar{Q}$ is dominant for heavy-quark production at high energies. Observation of a large helicity asymmetry in c- and b-quark production would unambiguously signify large gluon polarization. It is likely that we will have some primitive knowledge of gluon helicity at large x by the time a vertex detector is fielded by PHENIX. However, the ability to unambiguously detect open-charm and bottom production in p-p collisions would greatly extend the range in Bjorken-x of gluon helicity measurements to lower x values. A byproduct would be the first measurements of the total

charm and beauty crossections at these energies, which are important to the heavy-ion program.

Micro-vertex detectors have been successfully operated by CDF and D0 in 1.8 TeV p-p̄ collisions at Fermilab for several years as well for the LEP program at CERN. Thus micro-vertex detection in 200-500 GeV p-p collisions at RHIC should be feasible.

IV. Open-charm production in proton-nucleus collisions

Charm production is expected to be large in heavy-ion collisions at RHIC, large enough perhaps for as many as 5 to 10 cc̄ pairs to be created in each central collision. The charm quark plays a special role in the minds of many who try to understand the transition from the initial collision of highly relativistic heavy-ions to possible new states of matter that could be formed a short time later. The c quark is a negligible constituent of a nucleus, so all charmed particles found by vertex detection or by other means carry information on the earliest stages of particle production. In addition, the charm quark has a reasonably heavy mass (≈ 1.2 GeV), heavy enough to hope that perturbative QCD can provide an accurate guide to the initial conditions. And, of course, there are fundamental arguments that the most famous and easily observed bound state of the cc̄ spectrum, the J/ψ, can not exist in a QGP, thus making the suppression of the J/ψ a (apparently) most robust signal for the creation of this fabled new state of matter.

It is perhaps remarkable then that almost nothing is known about the way that charm quarks or charmed hadrons interact in normal nuclei. There is only one measurement of the nuclear dependence of open-charm production, an experiment led by P-Division physicists at Fermilab in the early 1990s [2,4]. This measurement, an experimental tour-de-force at the time, showed no evidence of charm suppression in proton-nucleus collisions. This is in stark contrast to the very large suppression of the J/ψ resonance under similar conditions. Measurements of open-charm in p-nucleus collisions, relative to p-p collisions, will provide essential input to our understanding of gluon shadowing in nuclei, parton energy loss in nuclear matter, etc.

V. Search for the quark-gluon plasma

The PHENIX experiment at RHIC is designed to detect a variety of signals emanating from the QGP, including the suppression of J/ψ production, production of thermal dileptons, thermal charm decays, etc. These signals of plasma formation, while on firm theoretical ground, are all subject to backgrounds from normal nuclear effects such as shadowing of nuclear parton distributions, uncertainties in the total charm crossection and so on. Thus, detailed knowledge of these nuclear effects is needed before one can reliably detect the presence of the QGP.

A primary goal of PHENIX is to detect color-screening suppression of J/ψ production in a QGP. This effect, analogous to Debye-screening in atoms, occurs when the color charge

of the free quarks and gluons screens the attractive force between the charm and anti-charm quarks that would normally form J/ψ's. This results in fewer J/ψs being formed, with the charm quarks hadronizing into D mesons instead.

Unfortunately, J/ψ production is also suppressed in proton-nucleus collisions, where a QGP cannot be formed. P-25 has led a series of experiments at Fermilab which first mapped out the nuclear suppression of the J/ψ, whose magnitude surprised the physics community. Currently there is no successful theoretical explanation of these nuclear effects, with a variety of competing mechanisms having been proposed. Even the magnitude of the J/ψ total crossection is not understood!

While PHENIX plans to record proton-nucleus data, untangling these varied mechanisms requires measurements beyond the current capabilities of the experiment. A measurement of the open-charm (D meson) crossection is needed to differentiate between initial-state nuclear effects, which would affect J/ψ's and D's in a similar way, in contrast to final-state effects, which would only affect the J/ψ. Initial-state effects include shadowing of the gluon distributions, energy loss of the incoming gluon, etc. Final state effects include dissociation of the J/ψ by scattering off the remnant nucleus, etc. Open-charm data are also required to test for the presence of thermal charm production in the plasma.

VI. Silicon Vertex Detector Design

The primary technical purpose for any vertex detector is to measure the tracks in an event with sufficient precision so that it is possible to distinguish between those from the primary vertex located at the interaction point and those from secondary vertices due to the decay of heavy quarks. Once this is achieved, it is then possible to pursue a vast range of physics related to flavor tagging as described above. In practice, at many large detectors both here and abroad, the specific choices of technologies and designs depends on the details of the beam energy and size, particle rapidity and multiplicity distributions, etc. No one solution covers all situations. Each vertex detector was custom designed which naturally leads to high costs and long development and construction times. For the PHENIX application discussed here we are also obligated to pursue a custom design that is tailored to the characteristics of the RHIC beam and PHENIX detector. However, with the number of vertex detectors growing, we believe there is a good chance that one can utilize past developments of electronics and sensors to streamline the R&D process and arrive at a cost effective solution that will meet the needs of PHENIX.

The vertex resolution requirements are dictated by the physics processes being studied. For open-charm detection in the PHENIX central arms, the D→K+π decay channel is the most promising, having branching ratios of 3.9% and the proper decay distance is $c\tau = 124$ microns. In the case of the muon arms, the important channel is a semi-leptonic decay to a muon (D→μ+X) with branching ratio ~19% and $c\tau = 318$ microns. These small decay lengths lead one to require an impact parameter resolution of much better than 100 microns and therefore spatial resolution of a few tens of microns. In addition, the detectors must be able to handle multiplicities of up to a few thousand particles per unit

rapidity. This demands a high degree of granularity so that the occupancy of each detector cell is kept to a few percent. These two requirements, excellent spatial resolution and high granularity, point to silicon detectors as the technology of choice. Indeed, all of the existing vertex detectors utilize silicon technology in the form of pixels, strips, silicon drift, or a combination of these as the innermost elements.

The SLD experiment at SLAC has perhaps one of the most ambitious vertex detectors in existence. It is made entirely of charge-coupled-devices (CCD's), a silicon pixel technology, with a total of 307 million pixels. The detector has three concentric layers of CCD's (2500 pixels per mm^2) at radii of 28mm, 38.2mm, and 48.3mm. Design considerations for this detector included radiation damage due to the close proximity to the beam pipe, support structures to maintain the position of the detectors, alignment systems to correct for any motion, and a cooling system to maintain the detector at 190 K. In a recent run the single-track spatial resolution was 5.4 microns including the intrinsic resolution and alignment errors. The impact parameter resolution was 14 microns in r-phi and 26.5 microns in rz. These values allowed for B meson tagging with 45% efficiency and 99% purity. Charm is more difficult than B's so the corresponding values will be less.

The ALICE experiment at the CERN Large Hadron Collider is a heavy-ion experiment that utilizes all three silicon technologies in their vertex detector. The innermost layer is pixels followed by silicon strips and finally by silicon drift. The choice of pixels as the innermost element is for high resolution and granularity, while the silicon strip and drift in the outer portion is to help in track reconstruction and to reduce the overall cost. The intrinsic spatial resolutions of these detectors are 12, 35, and 15 microns, respectively in r-phi and 100, 23, and 730 microns in z. The maximum occupancy for each type of detector is 2.1 to 4.0%. The detector is in the form of a barrel with a pair of each type of detectors at different radii. The pixel detectors are at 4.0 and 7.0 cm radius, the strip detectors are at 14.9 and 23.8 cm, and the silicon drift is at 38.5 and 43.6 cm.

The STAR detector at RHIC has recently installed a silicon vertex detector that uses silicon drift technology. It is designed to handle 2500 particles per event for rapidities between -1 and +1. The detector has three concentric barrels at 6, 10, and 15 cm radius and is 44 cm long. Prototype detectors achieved spatial resolutions of 10 microns in the anode readout and 20 microns in the drift component. By using all silicon drift technology, the STAR group reduced the cost, but the detector still cost $7 million for 0.7 m^2 of silicon. Other silicon vertex detectors at Fermilab use all strip technology, while at ATLAS a combination of pixel and strip technology is employed. Comparable resolutions are obtained to those above. Generally, the goal for all of these detectors is to begin tracking as close to the beam pipe as possible and to space the barrels so that the lever arm is optimized for impact parameter resolution. One of the biggest drawbacks to pixel and drift technology is the length of time to read out the electronics. The STAR detector has a conversion time of 160 μs and the SLD detector readout is limited to 2 MHz for 309 million pixels. To decrease the readout times one must read more of the detector out in parallel, but this drives up the cost. All of these detector designs were a compromise between performance and cost.

The goal of this proposal is to develop a design for a silicon vertex detector for PHENIX to be used in conjunction with the muon arms to allow detailed study of heavy quarks. Rather than a barrel geometry, the requirement is for disks in the forward direction where the muon arms cover 1.2 -2.4 in rapidity. Significant design issues include contending with the large interaction diamond, 20 cm, a beam spot larger than at the LHC (15 microns) or SLAC (1.5 microns) and a large range in the multiplicities for Au-Au collisions versus p-p. In addition, the PHENIX DAQ and common FEE architecture require a readout time less than 40 μs. We will strive to design a detector that will provide better than 20 micron impact parameter resolution yet maintain a moderate cost.

Proposed work plan:

The design will proceed in three steps:

I. Using GEANT and appropriate event generators, arrive at the design requirements in terms of angular coverage, placement of disks, and spatial resolution needed.

II. Canvas the available silicon technologies and electronics to define what will satisfy the design requirements from 1 above.

III. Prototype the detector and electronic choices and interface to the PHENIX DAQ.

At the same time a conceptual design of the ancillary support structures and cooling will be done.

Relationship to other projects and prospects for new support into the laboratory in the future based on this work:

This proposal has a strong connection to LANL's existing NPP program and previous work done at Fermilab and the SSC. The PHENIX program has brought significant R+D and construction funds to LANL in the past. If successful, this proposal is likely to bring additional capital construction funds from DOE for a new micro-vertex detector for PHENIX .

Funding breakout:
- $250K for FY02, FY03 and FY04. No M+S needed in FY02.
- FY03, Phase III will also require some capital equipment funds.

Specialist Reviewers :   Sam Aronson - BNL, Carlos Lourenco - CERN.

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